ANALOG AVENUE

Tech Notes

Measuring Temperatures Twice for Accuracy

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There are a variety of temperature sensors on the market, all of which meet specific application needs, with the most common including the thermocouple, resistive temperature detector (RTD), thermistor, and silicon-based sensors. But of all of these temperature sensors, the thermocouple is the only element that holds the esteemed position of requiring a secondary temperature sensing system to ensure that an absolute temperature measurement is taken.

What Thermocouples are Made Of

Thermocouples are a two-wire assemblies constructed of two dissimilar metals such as Chromel and Constantan (Type E) or Nicrosil and Nisil (Type N). The two dissimilar metals are bonded together on one end of both wires with a solder bead. This bead is exposed to the thermal environment of interest. If there is a temperature gradient between the bead and the other ends of the thermocouple wires, a voltage will appear between the two wires at the open ends. This voltage is commonly called the thermocouple's emf (electromotive force.) This emf changes with temperature without either current or voltage excitation. If the difference in temperature between the two ends (the solder bead Vs. the unsoldered ends) of the thermocouple changes, the emf will change as well.

There are as many varieties of thermocouples as there are metals, but some combinations work better than others. The list of thermocouples shown in Table 1 below are most typically used in industry and their behaviors have been standardized by the National Institute of Standards and Technology (NIST.) The particular document from this organization that is pertinent to thermocouples is the NIST Monograph 175, "Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90." Manufacturers use these standards to qualify the thermocouples that they ship.

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Thermocouple Type	Conductors	Temperature range (°C)	Seebeck Coefficient (@ 20°C)	Application Environments
E	Chromel (+), Constantan (-)	-200 to 900	62mV/°C	oxidizing, inert, vacuum
J	Iron (+), Constantan (-)	0 to 760	51mV/°C	vacuum, oxidizing reducing, inert
T	Copper(+), Constantan (-)	-200 to 371	40mV/°C	corrosive, moist, subzero
K	Chromel(+), Alumel (-)	-200 to 1260	40mV/°C	completely inert
N	Nicrosil(+), Nisil (-)	0 to 1260	27mV/°C	oxidizing
B	Platinum(30% Rhodium) (+), Platinum (6% Rhodium) (-)	0 to 1820	1mV/°C	oxidizing, inert
S	Platinum(10% Rhodium)(+), Platinum (-)	0 to 1480	7mV/°C	oxidizing, inert
R	Platinum (13% Rhodium(+)), Platinum (-)	0 to 1480	7mV/°C	oxidizing, inert

Table: The most common thermocouple types are shown with their standardized material and performance specifications. These thermocouple types are fully characterized by the American Society for Testing and Materials (ASTM) and specified in IST-90 units per NIST Monograpgh 175.

Designing the Reference Temperature Sensor

The signal path of the thermocouple circuit is illustrated in Fig. 1 (below.) The elements of the path include the thermocouple, absolute temperature element, analog gain cell, ADC and the reference temperature block (also known as the isothermal block.) Thermocouple #1 is the thermocouple that is at the site of the temperature measurement. Thermocouples #2 and #3 are formed as a consequence of the wires of thermocouple #1 connecting to the copper traces of the PCB.

An absolute temperature reference is required wherever a thermocouple is used to sense temperature. The reference is used to remove the emf error that is created by thermocouples #2 and #3 in Fig. 1 where the isothermal block is configured so that these thermocouples are kept at the same temperature as the absolute temperature sensing device. This can be done by keeping the circuitry in a compact area, analyzing the board for possible hot spots, and identifying thermal hot spots in the equipment enclosure. With this configuration, the known temperature of the copper junctions can be used to determine the actual temperature of the thermocouple bead.

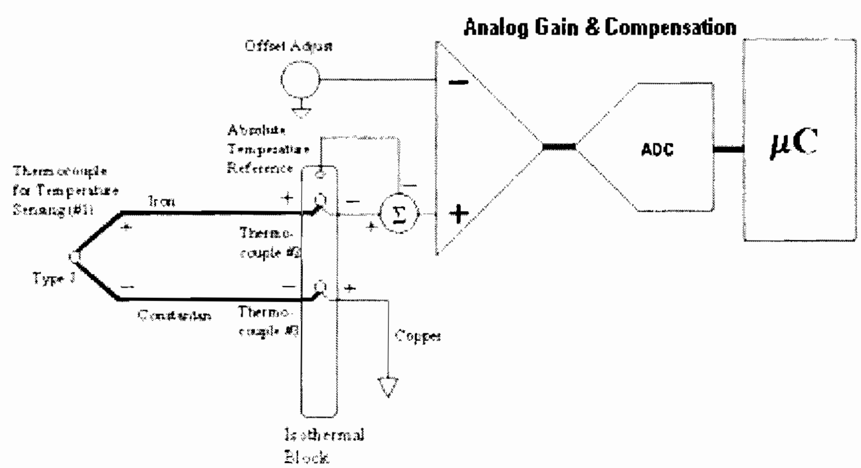

Fig1: A typical conditioning path for the thermocouple sensing circuit. The sensing element is thermocouple #1. Thermocouple #2 and #3 are formed with the temperature sensing element and the copper traces of the PCB

In Fig. 1, again, the absolute reference temperature is sensed and then subtracted from the thermocouple voltage. This style of compensation is implemented in hardware; or, the absolute reference temperature can be directly sensed and subtracted in software. The hardware solution can be designed to be relatively error free, but more than likely it has slight linearity errors, as will be discussed later. The software correction can be more accurate because of the computing power of the processor. The trade-off for this type of calibration is

computing time.

The relationship between the thermocouple bead temperature and zero degrees C is published in the form of look-up tables or coefficients of polynomials in the NIST publication mentioned earlier. If the absolute temperatures of thermocouples #2 and #3 (Fig. 1, again) are known, the temperature at the test site (thermocouple #1) can be calculated.

Isothermal Block-Error Correction Hardware Implementations

Many techniques can be used to sense the reference temperature on the isothermal block; five of which are discussed here. The first example uses a second thermocouple. It is used to sense ambient at the copper connection and configured to normalize the resultant voltage to an absolute temperature. A second example uses a standard diode to sense the absolute temperature of the isothermal block. This is done by using its negative temperature coefficient of -2.2mV/°C, which is a characteristic of the diode. Thirdly, a thermistor temperature sensor is shown as the reference temperature device. As with the diode, most thermistors have a negative temperature coefficient. The thermistor is a little harder to use because of its tendency to non-linearities, but the price is right. Another technique discusses an RTD (resistance temperature detector) as the reference temperature sensor. These sensors are best suited for precision circuits. And, finally, the silicon temperature sensor is briefly discussed.

Using a Second Thermocouple for a Reference

A second thermocouple can be used to remove the error contribution of all of the thermocouples in the circuit. A circuit that uses this technique is shown in Fig. 2.

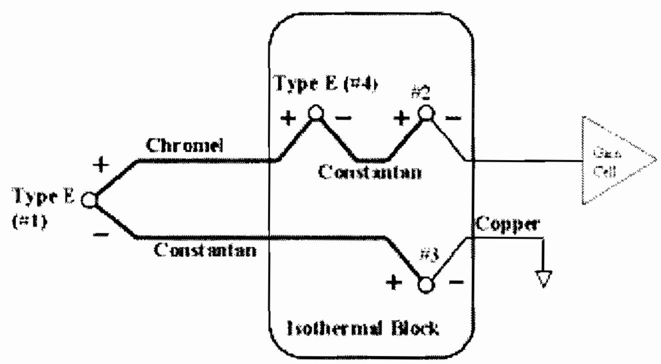

Fig2: The temperature on the isothermal block can be sensed with the same type thermocouple as is positioned at the measurement site. This configuration zeros out the errors introduced into the signal path that are caused by thermocouple #2 and #3.

In this circuit example a Type E thermocouple is chosen to sense the unknown temperature at the measurement site. The Type E thermocouple is constructed of Chromel (a combination of Nickel and Chromium) on its positive side and Constantan on its negative side. A second Type E thermocouple is included in the circuit. It is positioned on the isothermal block and installed between the first thermocouple and the signal-conditioning circuit. The polarity of the two Type E thermocouples is critical so that the Constantan on both of the thermocouples are connected together.

From this circuit configuration, two additional thermocouples are built, both of which are constructed with Chromel and copper. These two thermocouples have a voltage-to-temperature response that opposes one another in the circuit. If both of these newly-constructed thermocouples are at the same temperature, they will cancel each other's temperature-induced errors. The two remaining Type E thermocouples generate the appropriate emf that identifies the temperature at the site of the first thermocouple.

This design technique is ideal for instances where the temperature of the isothermal block has large variations, or the first derivative of the voltage-Vs.-temperature relationship of the selected thermocouple has a sharp slope (Fig. 3.) Thermocouples that fit into this category in the temperature range from 0 °C to 70 °C are Types T and E.

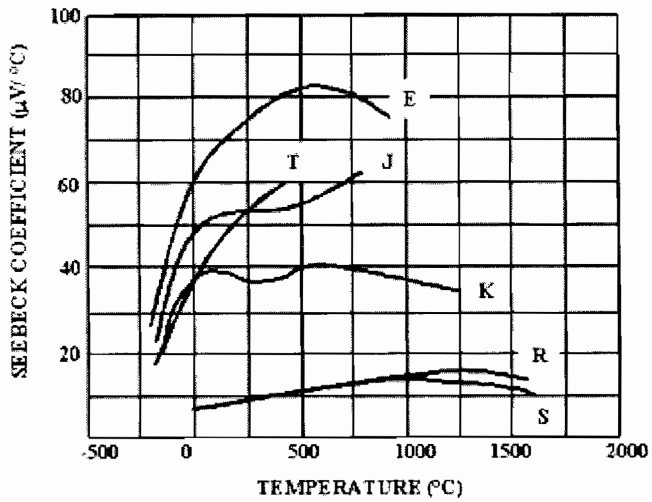

Fig3: Thermocouples do not have linear responses in EMF voltage due to temperature changes. This graph shows the first derivative of this behavior in the form of the change in temperature gradient of the thermocouple with the change in temperature.

The error calculation for the compensation scheme in Fig. 2 is: V_{TEMP} = +emf3 + emf1 - emf4 - emf2,

where,

emf1 is the voltage drop across the Type E thermocouple at the test measurement site.

emf2 is the voltage drop across a Copper/Constantan thermocouple, where the copper metal is actually a PCB trace.

emf3 is the voltage drop across a Copper/Constantan thermocouple, where the copper metal is actually a PCB trace.

emf4 is the voltage drop across a Type E thermocouple on the isothermal Block V_{TEMP} is the equivalent emf of a Type E thermocouple, #1, referenced to 0 °C.

The temperature reference circuitry is configured to track the change in the Seebeck Coefficient (Fig. 3) fairly accurately. The dominating errors with this circuit will occur as a consequence of less than ideal performance of the Type E thermocouples, variations in the purity of the various metals, and an inconsistency in the temperature across the isothermal Block.

Diode Temperature Sensing

Diodes are useful temperature sensing devices where high precision is not a requirement. Given a constant current excitation, standard diodes, such as the IN4148, have a voltage change with temperature of approximately -2.2 mV/°C. These types of diodes will provide fairly linear voltage-Vs.-temperature performance. However, from one part to another they may have variations in absolute voltage drop across the diode as well as differences in temperature drift.

This type of linearity is not well suited for thermocouples with wide variations in their Seebeck Coefficients over the temperature range of the isothermal block (Fig. 3, again.) In that case, thermocouple Types K, J, R and S may be best suited for the application. If the application requires more precision in terms of linearity and repeatability from one part to another than an off-the-shelf diode, there are parts available that are designed specifically for temperature sensing applications.

A single supply circuit that uses a diode for the absolute temperature sensor is shown in Fig. 4. A voltage reference is used in series with a resistor to excite the diode. The diode change with temperature has a negative coefficient, but the magnitude of this change is much higher than the change of the collective thermocouple junctions on the isothermal block. This problem is solved by putting two series resistors in parallel with the diode. In this manner, the change of -2.2 mV/°C of the diode is attenuated to the Seebeck Coefficient of the thermocouple on the isothermal block. The Seebeck Coefficient of the thermocouples on the isothermal block are also equal to the Seebeck Coefficient (@ isothermal block temperature) of the thermocouple that is being used at the test site. Fig. 4 shows some recommended resistance values for various thermocouple types and excitation voltages.

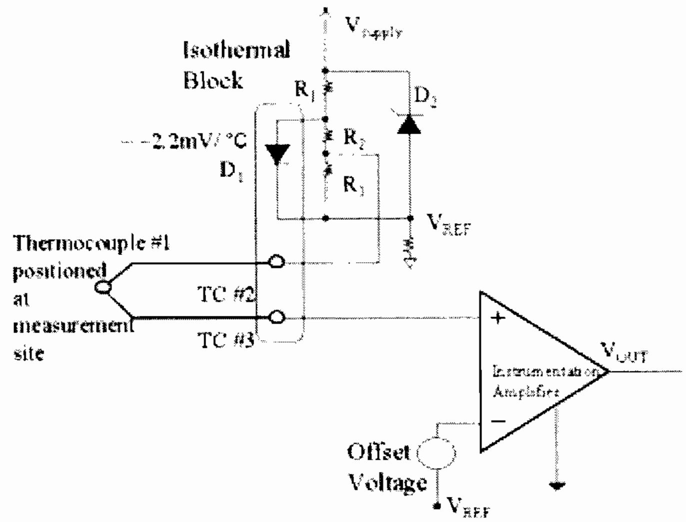

Fig4a: TA diode can be used to reduce the errors of thermocouple(TC) #2 and #3 that are introduced into the temperature sensing system. In this circuit, changes between VSUPPLY and VREF need to be kept as small as possible.

Thermocouple Type	Seebeck Coefficient (@20°C)	V_{cc} (V)	R_1 (ohms)	R_2 (ohms)	R_3 (ohms)
J	51 mV/°C	4.096	9.76k	4.22k	100
J	51 mV/°C	5.0	12.1k	4.22k	100
J	51 mV/°C	10.0	27k	4.22k	100
K	40 mV/°C	4.096	9.76k	5.36k	100
K	40 mV/°C	5.0	12.1k	5.36k	100
K	40 mV/°C	10.0	27k	5.36k	100
R	7mV/°C	4.096	9.76k	31.6k	102
R	7mV/°C	5.0	12.1k	31.6k	102
R	7mV/°C	10.0	27k	31.6k	102
S	7mV/°C	4.096	9.76k	31.6k	102
S	7mV/°C	5.0	12.1k	31.6k	102
S	7mV/°C	10.0	27k	31.6k	102

Fig4b

This circuit appears to provide a voltage excitation for the diode. This is true, but the ratio of the voltage excitation to voltage drop changes with temperature minimize linearity errors. Of the three voltage references (D2) chosen in Fig. 4, a constant 10-V drop across D2 provides the most linear results. It might also be noticed that changes in the D2 voltage will also change the current through the diode. This being the case, a precision Zener reference is recommended for higher-accuracy applications.

Thermistor Circuits

Thermistors are resistive devices that (generally) have a negative temperature coefficient (NTC.) These inexpensive sensors are ideal for moderate precision thermocouple sensing circuits when some or all of the non-linearity of the thermistor is removed from the circuit.

The NTC thermistor's non-linearity can be calibrated out with software or hardware techniques. The software techniques are more accurate although hardware techniques are usually more than adequate. Fig. 5 shows a thermistor in series with an equivalent resistor and voltage excitation. In this circuit, the change in voltage with temperature is about -50 mV/°C. This temperature coefficient is too high but a resistor divider (R1 and R2 in Fig. 5) can easily provide the required temperature coefficient dependent on the thermocouple Type. As is, with the diode temperature sensor circuit in Fig. 4, the voltage drop across the thermistor, R1, and R2 must be kept constant over time and temperature. A Zener reference is again recommended.

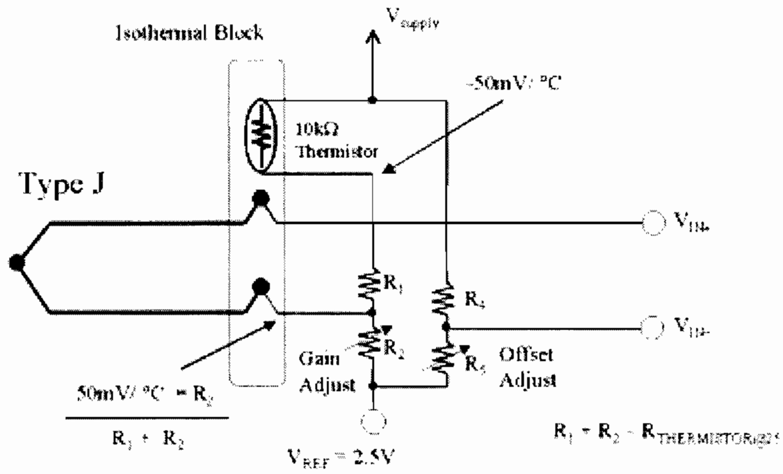

Fig5: If the summation of R1 and R2 is equal to the nominal resistance of the thermistor at 25°C, resistance will be most linear between 0 to 50°C.

Alternatively, the NTC thermistor can be excited with a current source. Low-level current sources, such as 20 µA, are usually recommended to minimize self-heating problems. Fig. 6 compares the linearity with current excitation to voltage excitation. As shown, a thermistor that is operated with current excitation is fairly non-linear (requiring a 3rd order polynomial equation for corrections.) With this type of circuit, software calibration would be needed, and although somewhat cumbersome, this type of excitation scheme can be more accurate. On the other hand, a voltage excitation does have fairly linear operation over a limited temperature range (0 °C to 50 °C.) Taking advantage of this linear region reduces software calibration overhead significantly.

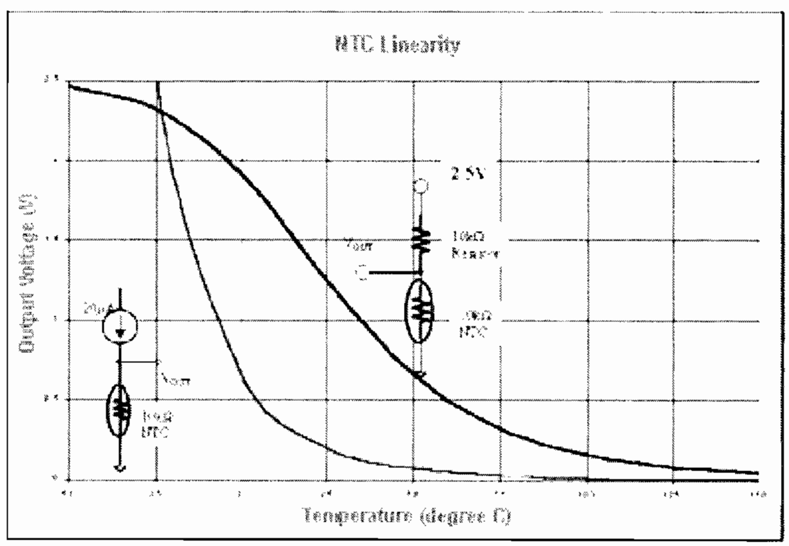

Fig6: The non-linearity of the thermistor is most prevalent with a current excitation. In contrast, the combination of a series voltage source and resistor create a region of linearity between 0 and 50°C.

RTD Sensor Circuits

Typically an RTD would be used on the isothermal block if high precision is desired. The RTD element is nearly linear so employing linearization algorithms for the RTD is usually overkill. The most effective way to get good performance from an RTD is to excite it with current. Both Figs. 7 and 8 show circuits that can be used for this purpose.

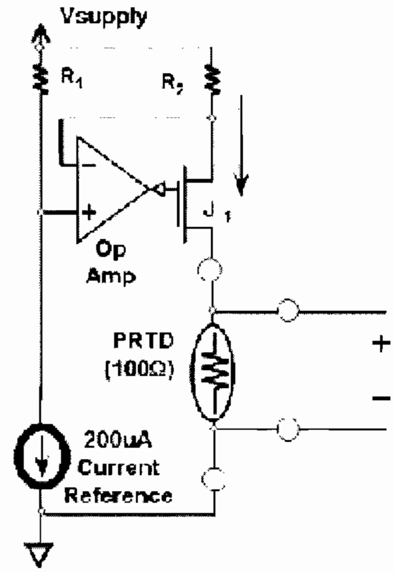

Fig7: A 200µA current source is gained to a 1mA current cource that excites the RTD temperature sensing element. Current excitation for the RTD element is the most effective way to get good linear performance of the RTD resistance versus temperature.

In Fig. 7, a precision current reference is gained by the combination of R1, R2, J1, current reference and an op amp. The current reference generates a 200 µA precision current source. That current is pulled across R1 forming a voltage drop for the power supply down to the non-inverting input of the op amp. The op amp is used to isolate R1 from R2, while translating the voltage drop across R1 to R2. In this manner, the 200 µA current from the current reference is gained by the ratio of R1/ R2. J1 is used to allow the voltage at the top of the RTD element to float, dependent on its resistance changes with temperature. The RTD element should be sensed differentially with the voltage across this output proportional to absolute temperature.

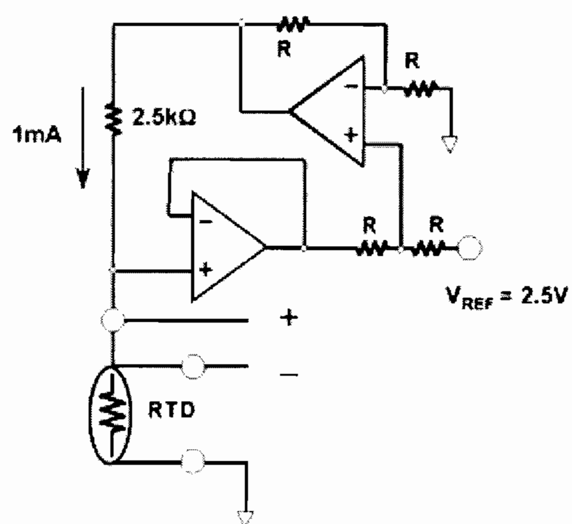

Fig8: A combination of a voltage reference and two operational amplifiers generate a 1mA current source that excites the RTD temperature sensing element.

In Fig. 8 a voltage reference is used to generate a 1 mA current source for the RTD element. The advantage of this configuration is that the voltage reference can be used elsewhere, allowing ratiometric calibration techniques in other areas of the circuit.

The RTD sensor is best suited for situations where software isothermal block error correction is used exclusively. Both of the RTD circuits (Figs. 7 and 8) will output a voltage that is fairly linear and proportional to temperature. This voltage is then used by the processor to convert the absolute temperature reading of the isothermal block back to the equivalent emf. This can be performed by the processor with a look-up table or a polynomial calculation for higher accuracy. The calculated emf is then subtracted from the voltage measured across the sensor/isothermal block combination. In this manner, the errors from the temperature at the

isothermal block are removed.

Silicon Sensor

Silicon temperature sensors are differentiated from the simple diode because of their complexity. A silicon temperature sensor is an integrated circuit that uses the diode as a basic temperature-sensing building block. It conditions the temperature response internally and provides a usable output such as 0 to 5 V, digital 8- or 12-bit word, or temperature-to-frequency. The accuracy of these devices is not as good as the thermistor or RTD, but the output signal format offers a convenience for the microprocessor.

These devices are similar to the RTD in that they are not used for hardware calibration. The output of this type of device is used by the processor to remove the isothermal block errors.

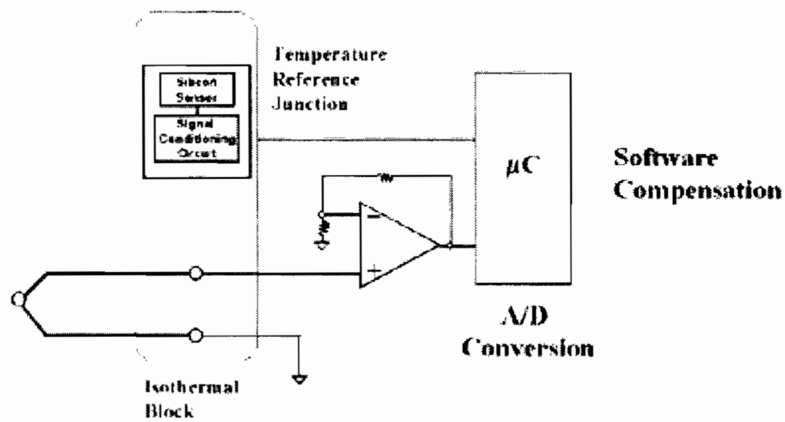

Fig9: Silicon integrated temperature sensing circuits can be used to measure the temperature on the isothermal block. With this strategy, the uC removed the isothermal block errors and linearizes the thermocouple EMF voltage to obtain the absolute temperature at the thermocouple sensing element.

Two Temperature Measurements Equals Twice as Good!?

The thermocouple does a reasonably good job in sensing temperatures in hostile environments, be it atmospheric or high temperatures. But in all applications using the thermocouple, a second temperature sensing channel needs to be designed in order to determine the absolute temperature of the measurement site. Without this second temperature sensing device, the thermocouple circuit will only report the difference in temperature between the various thermocouples in the circuit. There are a variety of sensors to choose from that will perform this task. The use of these sensors, coupled with the power of the microcontroller, is the most effective when trying to achieve an accurate, absolute temperature measurement.

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